Nitrogen Absorption and Desorption by Iron and Stainless Steels during Laser Welding(レーザ溶接過程における鉄及びステンレス鋼の窒素吸収・放出)

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論文内容要旨

Chapter 1 Introduction

The influence of nitrogen in steels has been a subject of investigation for at least three decades. The presence of nitrogen in steels has a beneficial or a deleterious influence on the properties of the materials, depending on the concentration, the thermal processing of the steel, and the presence of alloying elements. In mild steel, low alloy steels and ferritic stainless steels (and martensitic steels), nitrogen is generally considered to be an undesirable impurity, causing porosity and forming brittle nitrides. It is therefore important to limit nitrogen absorption in these steels. This poses a particular problem during welding. In austenitic stainless steels, however, nitrogen has been considered as an element that improves many properties such as corrosion resistance, strength, creep strength, toughness, etc. The development of steels with high nitrogen content far in excess of thermodynamic equilibrium is one example of the successful application of nitrogen. Austenitic stainless steels can accommodate significantly higher levels of nitrogen in solution. In nitrogen-alloyed austenitic stainless steel, the most important is not often nitrogen absorption, but nitrogen desorption to the arc atmosphere, resulting in lower nitrogen levels in the weld metal. A decrease in nitrogen concentration in the region of the weld has a detrimental effect on the mechanical properties and corrosion resistance of the joint.

Laser welding has recently received increasing attention and is expected to have a great impact on fabrication and manufacturing industries in welding of steel structures within the next decade due to its high energy density and low heat input compared with conventional fusion techniques. The interaction between laser beam and material may affect the nitrogen absorption, but has not been investigated well yet. In order to control nitrogen absorption and desorption from the molten pool during laser welding, a fundamental knowledge of the nitrogen absorption and desorption mechanism is necessary.

The main objective of the present study is to investigate the nitrogen behavior of iron and stainless steels during CO_2 and YAG welding in comparison with those during arc welding and that in a state of equilibrium in order to clarify the mechanism of nitrogen behavior during laser welding.

Chapter 2 Nitrogen Absorption and Desorption by Iron and Stainless Steels during CO_2 Laser Welding

In order to characterize the nitrogen behavior during laser welding, nitrogen content of iron, Fe-20Cr-10Ni alloy and SUS329J1 duplex stainless steel weld metal during CO_2 laser welding in an atmosphere of an Ar-N_2 gas mixture was investigated in comparison with equilibrium data and those during arc welding. Additionally, the applicability of laser welding to high nitrogen steels in consideration of nitrogen behavior is also discussed.

The results show that the nitrogen absorption and desorption during CO_2 laser welding mainly occur in the upper part of the weld. The nitrogen absorption during CO_2 laser welding is much smaller than that during arc welding. Consideration of nitrogen behavior during CO_2 laser welding compared with behavior during GTA welding suggests that lower level of nitrogen absorption during CO_2 laser welding is attributable to the lower promotion of monatomic nitrogen and also to the effect of metal vapor generated during laser welding that impedes the nitrogen from coming in contact with the surface of the molten metal in the keyhole.

From the view of nitrogen behavior, laser welding may have applicability to high nitrogen steels.

Chapter 3 Nitrogen Absorption by Iron and Stainless Steels during YAG Laser Welding

Nitrogen absorption by iron, Fe-20Cr-10Ni alloy and SUS329J1 duplex stainless steel during YAG laser welding in an atmosphere of an Ar-N_2 gas mixture was investigated in comparison with equilibrium data and those during CO_2 laser welding and arc welding. As shown in Figure 1, the nitrogen content of YAG laser iron weld metal of was found to increase with the nitrogen partial pressure as did those during CO_2 laser and arc welding, although the nitrogen contents during YAG laser welding were slightly lower than those during CO_2 laser welding. The nitrogen contents during CO_2 and YAG laser welding were much smaller than those during arc welding.

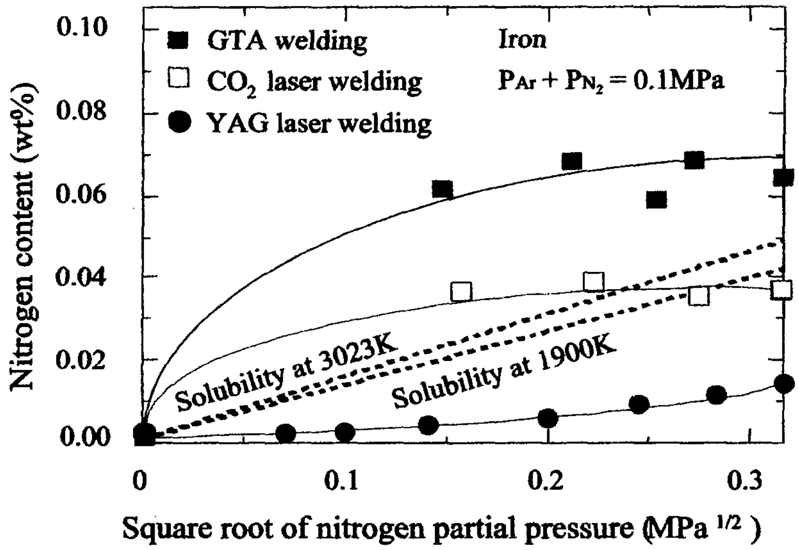

Figure 1 Comparison of nitrogen content of iron during CO_2 laser welding, arc welding, equilibrium calculation and YAG laser welding.

A discussion of difference in the nitrogen behavior during YAG laser and CO_2 welding suggests that the lower level of nitrogen absorption during YAG laser welding may be due to lesser amount of monatomic nitrogen in the atmosphere during YAG laser welding.

Chapter 4 Mechanism of Nitrogen Absorption of Steel Weld Metal during Laser Welding

As shown in Chapter 2 and 3, the nitrogen absorption in the weld metal depends on the welding methods. However, at the present, there is too few experimental data about the nitrogen absorption during laser welding to examine the absorption mechanism. In this chapter, monochromatic images of a specific spectrum line emitted by monatomic nitrogen and iron during CO_2 laser and arc welding were observed to clarify the distribution of monatomic nitrogen over the molten weld metal and the relationship between the nitrogen absorption and state of plasma. The monochromatic plasma photographs for the specific wavelengths of monatomic nitrogen and iron atom and the visible plasma image during CO_2 laser welding are shown in Figure 2. The welding direction is from left to right in Figure 2. The rear part of weld molten pool is in the left part of visible plasma image. The monatomic nitrogen image in Figure 2(b) is seen like a thin bar with about 3mm high. The position of monatomic nitrogen image is around the axis of laser beam, just over the keyhole. Meanwhile, the iron atom image shown in Figure 2(c) is about 2mm high and is concentrated around the open part of keyhole. Since the area of molten pool shown in Figure 2(a) is much larger than the existing area of plasma image, the part of the molten pool, which is not covered by plasma, is much large.

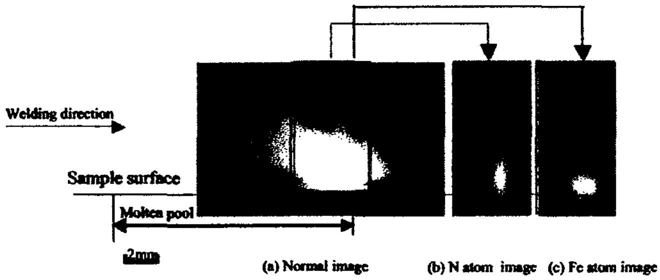

Figure 2 Monochromatic photographs of laser plasma formed during CO_2 laser welding:
(a) normal image, (b) N atom image, (c) Fe atom image.

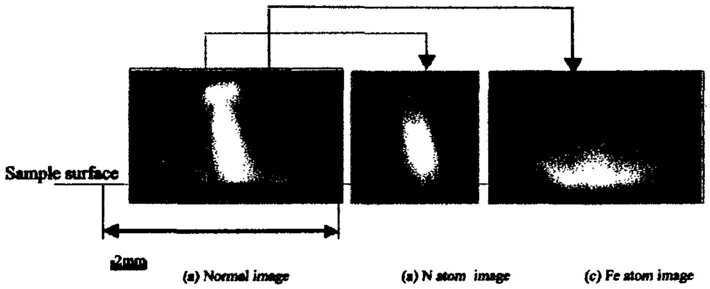

Figure 3 Monochromatic photographs of arc plasma formed during arc welding:
(a) normal image, (b) N atom image, (c) Fe atom image.

For comparison, the monochromatic plasma photographs for arc welding are shown in Figure 3. The apparent difference in the monochromatic photographs between CO_2 laser welding and arc welding is that the monatomic nitrogen widely exists over molten pool during arc welding. The existing area of monatomic nitrogen, which is just over the keyhole, is much smaller than the area of molten pool during CO_2 laser welding. So compared with arc welding, the reaction area between monatomic nitrogen and molten pool is small. This may be the reason for the less nitrogen absorption during CO_2 laser welding compared with arc welding, where large amount of monatomic nitrogen in present over the molten surface.

From plasma monochromatic photographs shown in Figure 2(b), the existing of monatomic nitrogen can be observed clearly. The contribution of monatomic nitrogen to nitrogen absorption of weld metals during CO_2 laser welding may account for the less nitrogen absorption during YAG laser welding due to much less monatomic nitrogen in the atmosphere. This will be discussed in chapter 5. Additionally, the existence of dense metal vapor during laser welding may also limit monatomic nitrogen to contact the surface of the molten pool in the keyhole, which also leads to less nitrogen absorption of weld metals during laser welding in comparison with that during arc welding. This is described in the following sections.

Chapter 5 Parameters of CO_2 Laser Welding on Nitrogen Absorption in Iron and Stainless Steels

In order to further understand the absorption mechanism, the effect of metal vapor and plasma state on nitrogen absorption was also investigated by changing the focus position of laser beam and the pressure of nitrogen atmosphere in the chamber during CO_2 laser welding.

The effect of the focus position on the nitrogen content of CO_2 laser weld metal of Fe-20Cr-10Ni alloy shows that the penetration shape shifted from keyhole to non-keyhole with increasing the defocus distance over the sample surface. Nitrogen contents of conduction mode weld metal are significantly higher than those of keyhole mode weld metal. The effect of welding speed on the nitrogen absorption in the welded metals in both penetration modes during CO_2 laser welding was also investigated. Although the penetration areas of both type penetration modes and the nitrogen contents in conduction mode weld metal decrease with the increase of welding speed, the nitrogen content in conduction mode weld metal is much higher than that in keyhole mode weld metal.

The above results prove that the nitrogen absorption during CO_2 laser welding mainly occurs on the surface of the molten pool.

For comparison, the effect of welding speed on nitrogen absorption during GTA welding was also investigated. By contrast to CO_2 laser welding, the nitrogen in conduction mode weld metal of Fe-20Cr-10Ni alloy is still less than that during GTA welding though the shape of cross-sections of weld metal is similar, and the nitrogen content in weld metal increases with the welding speed during arc welding.

The area of molten pool directly exposed to arc can become instantaneously supersaturated with nitrogen due to the high partial pressure of monatomic nitrogen, and subsequently the desorption of nitrogen will occur after the arc moves away. The increase in welding speed under arc leads to the decrease in the melting time of weld metal, the decrease in the nitrogen desorption time. Thus, the nitrogen content in the arc-weld metal is controlled mainly by nitrogen desorption. Since nitrogen desorption time decreases with the increase in arc welding speed, the nitrogen content in the weld metal increases with the arc-welding speed. As for laser welding, the area ratio exposed to the monatomic nitrogen in the molten weld pool is much smaller than that of arc-welding, as seen in Figure 3, and also the partial pressure of monatomic nitrogen is low because of high partial pressure of iron vapor in the keyhole. The nitrogen content of weld metal can not reach the equilibrium value generally during laser welding of low nitrogen steels. Nitrogen absorption time decreases with the increase of welding speed. So the nitrogen content in the weld metal decreases with the welding speed. The nitrogen content in the weld metal is controlled mainly by nitrogen absorption.

In order to evaluate plasma state on nitrogen absorption during CO_2 laser welding, melt–run welding by the CO_2 laser was carried in the chamber where the pressure of nitrogen atmosphere decreasing from 0.1 to 0.00013 MPa, while keeping the other parameters constant. The results show that the nitrogen content in weld metal of all the materials used in this study under depressurized atmosphere increases with the nitrogen pressure.

Compared with the results in chapter 2 and 3, the nitrogen content in weld metal of all the materials used in this study under reduced atmosphere goes between the nitrogen content in the weld metal of the same materials in Ar-N_2 gas mixture of 0.1 MPa during CO_2 laser welding and YAG laser welding. Since the density and the temperature of plasma decrease when the pressure is reduced and the plasma disappears at low pressure, the dissociation of diatomic nitrogen into monatomic nitrogen is supposed to be difficult to occur during depressurized atmosphere. The lesser nitrogen content in weld metal at depressurized atmosphere than that with the same nitrogen partial pressure under 0.1MPa atmospheric pressure during CO_2 laser welding is consistant with the behavior of plasma at depressurized pressure during CO_2 laser welding. The good agreement of nitrogen content in reduced nitrogen atmosphere during CO_2 laser welding with that obtained during YAG laser welding within the range of low nitrogen (partial) pressure is also consistent with what have been discussed in previous work that plasma is difficult to occur during YAG laser welding. The smaller nitrogen absorption during YAG laser welding is attributed from less existence of monatomic nitrogen compared with that during CO_2 laser welding.

Chapter 6 Summary

The results of the present study and some considerations on future works are summarized in this chapter.

論文審査結果の要旨

近年、高出力レーザの開発が進み、レーザ溶接が厚鋼板へも適用さてはじめている。レーザ溶接は、溶け込みが深く溶融幅と熱影響部が狭く溶接変形や残留応力が小さいなど多くの利点をもつ。しかし、不活性ガスシールドでレーザ溶接すると気孔が発生し易いことが問題となっている。その際、窒素ガスでシールドすると気孔が抑制される傾向があるが、その原因は明らかではない。また、高強度高耐食性を示すとして注目されている高窒素鋼の溶接に関して、アーク溶接では窒素量の低下と窒素による気孔発生など多くの問題があるが、レーザ溶接は短時間の小入熱溶融溶接であることから、高窒素鋼の溶接法としての可能性を秘めている。このような背景から、鋼のレーザ溶接過程における窒素の吸収および放出挙動を解明することが、レーザ溶接の工業的発展に重要と考えられるが、窒素の挙動に関する情報はほとんどないのが現状である。そこで、本研究では、純鉄及び高窒素鋼を含む種々の鋼のレーザ溶接過程における窒素吸収・放出挙動を詳細かつ系統的に調べ、レーザ溶接過程の窒素吸収および放出機構を解明し、レーザ溶接の発展に資することを目的として行われた。

論文は全編6章で構成されている。

第1章は序論であり、本研究の背景および目的を述べている。

第2章では、CO_2レーザ溶接過程における鉄、ステンレス鋼および高窒素鋼の窒素吸収・放出挙動を平衡状態及びアーク溶接の場合と比較検討し、アーク溶接より窒素吸収・放出が少ないことを示した。

第3章では、YAGレーザ溶接過程における鉄およびステンレス鋼の窒素吸収挙動を平衡状態、CO_2レーザ及びアーク溶接の場合と比較検討し、YAGはCO_2レーザ溶接よりさらに窒素吸収が少ないことを明らかにした。

第4章では、レーザおよびアーク溶接における溶融池付近のプラズマ状態を分光画像によって観察し、単原子窒素ガスと金属蒸気の分布状態から、雰囲気の単原子窒素ガスが主に窒素吸収を支配していることを示した。

第5章では、減圧雰囲気、焦点位置及び溶接速度を変化させてレーザ溶接した場合の溶接金属の窒素量の変化から、レーザ溶接では窒素吸収が、アーク溶接では放出が溶接金属の窒素量を主に支配していることを明らかにした。

第6章は本研究の結果をまとめた総括である。

以上要するに本論文は、レーザ溶接過程における鋼の窒素吸収・放出挙動とその機構を明らかにし、鋼のレーザ溶接に関する基礎的および実用的に重要な情報を提供しており、材料加工プロセス学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。